# Headquarters U.S. Air Force

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# Former George Air Force Base

HYDRUS Remediation Modeling
June 2016

# Proposed HYDRUS Application

- Use HYDRUS-2D model code in vertical profiles to simulate source area mass loading, vadose zone and groundwater flow and transport, and attenuation of organic compound plumes including LNAPL areas
- Replaces VLEACH and other analytical vadose zone models
- Model areas where there is potential for vadose zone contamination to affect groundwater and for Dieldrin colloidal transport
- No NAPL areas—FT019, FT082, SS083, others as needed
- NAPL area—SS030, ST067b, others as needed
- Dieldrin area—OT071
- Can provide source loading terms for 3D MODFLOW-SURFACT groundwater transport

# HYDRUS Model Code

- Finite element code with internal controls on transport numerical dispersion
- Originally developed by U.S. Dept. of Agriculture in 1998-1999 for simulation of flow and transport in vadose zone by Jirka (Jiri) Šimůnek, and M. Th. van Genuchten (creator of van Genuchten equation)
- Extended to include a wide variety of hydrogeologic conditions
- Calculates recharge from daily or hourly meteorological data
- HYDRUS solves the Richards equation for unsaturated/saturated flow

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi}{\partial z} - 1\right)\right]$$ (1D version)

*where K = hydraulic conductivity, $\theta$ = water content, $\psi$ = pressure head, z = elevation, t = time*

- Extensive solute transport modules including colloidal transport
- Heat transport accommodates heating and cooling of soil and recharge water
- Wide range of available flow and transport boundary conditions

# HYDRUS References

- HYDRUS 2D Code description: http://www.pc-progress.com/en/Default.aspx?h3d-description
- Numerous literature references on HYDRUS applications: http://www.pc-progress.com/en/Default.aspx?Downloads
- There is a HYDRUS to MODFLOW flow only package for linking MODFLOW and HYDRUS

# Why HYDRUS Code?

- Well vetted and peer reviewed in literature
- Hundreds of examples
- Not limited by analytical vadose zone model assumptions
- Robust solution algorithms for variably saturated simulations
- Colloidal transport simulation module
- Comprehensive user interface for model setup and output analysis
- Good user support from developers

# HYDRUS Limitations

- Simulates water flow and contaminant transport in variably saturated conditions—soil and vapor concentrations determined from partitioning model selected (e.g. equilibrium, non-equilibrium)
- Because HYDRUS simulates multi-phase flow and transport, model stability sensitive to initial conditions (typical of multi-phase models)
- Computationally very intensive, typical of multi-phase flow and transport models
- Currently implemented for 2D X-Z simulations, can be expanded to 3D with software upgrade
- 3D flow and transport simulations require long simulation run-times without parallel processing capabilities
- Solute transport solution may have small, minor concentration artifacts near steep concentration fronts in vadose zone

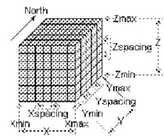
# Input Data

- Surface soil from SSURGO database
- Lithology, vadose zone, and groundwater inputs from profiles thru 3D models
- Meteorological data—CIMIS station 117 and NOAA Victorville pump station
- Unsaturated flow parameters
  - Site-specific data from OT071 drilling program—PTS vapor transport package (grain size, porosity, permeability, density, moisture content, foc)
  - van Genuchten parameters from published soil type databases using above results
- Vadose zone concentrations derived from current soil vapor concentrations and assume equilibrium partitioning between vapor, water, and soil
- LNAPL source loading derived from LNAPL well groundwater samples

# OU1 3D Lithology and Plume Data Analysis

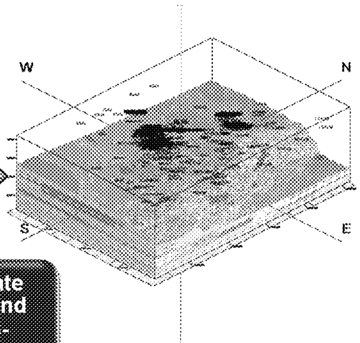
**Compile data into 3D database**
- Boring logs, analytical data, etc.

**Construct 3D volumetric "cube"**
- 3D gridding of data (various methods)




**Integrate existing surfaces**
- Topography, water level elevations, structural surfaces, etc.

**Final 3D "cubes"**




**Generate maps and cross-sections**

These are 3D models based on observed data and not a 3D numerical flow and transport model.



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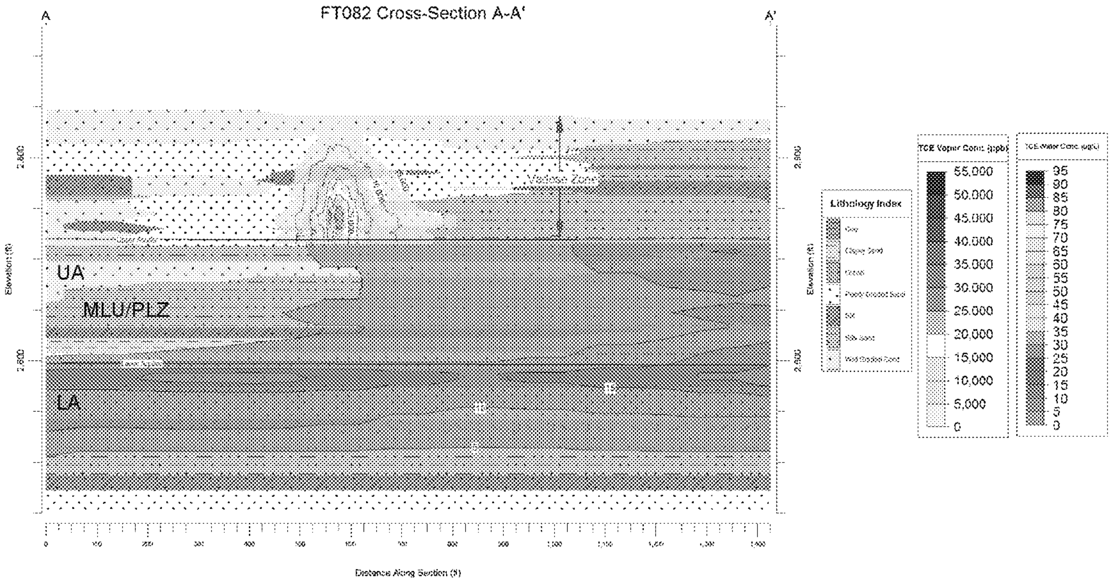
# Profile Cross-Section Example thru FT082

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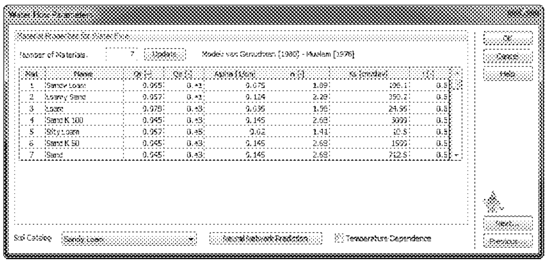
# HYDRUS Flow Input—Hydraulic Data

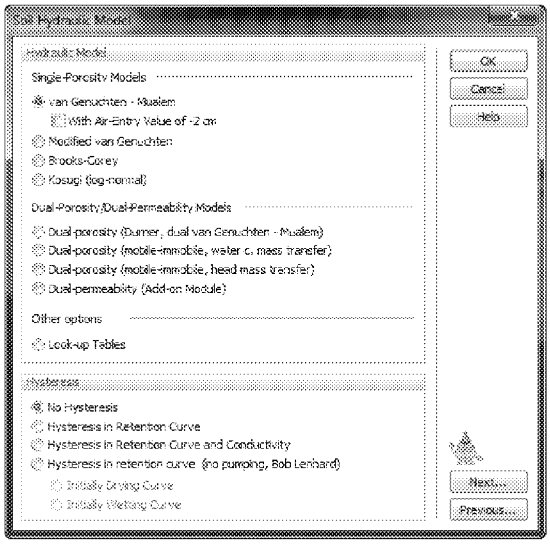
**Soil Type Parameters**

- **Hydraulic conductivity (Ks)**
- **Porosity (Qs)**
- **Residual saturation (Qr)**
- **Van Genuchten/Mualem parameters**



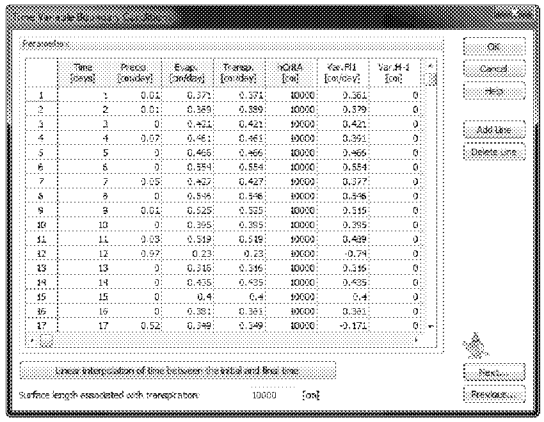

| Mat | Name | Qr [-] | Qs [-] | Alpha [1/cm] | n [-] | Ks [cm/day] | l [-] |
|---|---|---|---|---|---|---|---|
| 1 | Sandy Loam | 0.065 | 0.41 | 0.075 | 1.89 | 106.1 | 0.5 |
| 2 | Loamy Sand | 0.057 | 0.41 | 0.124 | 2.28 | 350.2 | 0.5 |
| 3 | Loam | 0.078 | 0.43 | 0.036 | 1.56 | 24.96 | 0.5 |
| 4 | Sand K 100 | 0.045 | 0.43 | 0.145 | 2.68 | 3000 | 0.5 |
| 5 | Silty Loam | 0.067 | 0.45 | 0.02 | 1.41 | 10.8 | 0.5 |
| 6 | Sand K 50 | 0.045 | 0.43 | 0.145 | 2.68 | 1500 | 0.5 |
| 7 | Sand | 0.045 | 0.43 | 0.145 | 2.68 | 712.8 | 0.5 |

**Variable Saturation Hydraulic Models**



# HYDRUS Flow Input—Meteorological Data

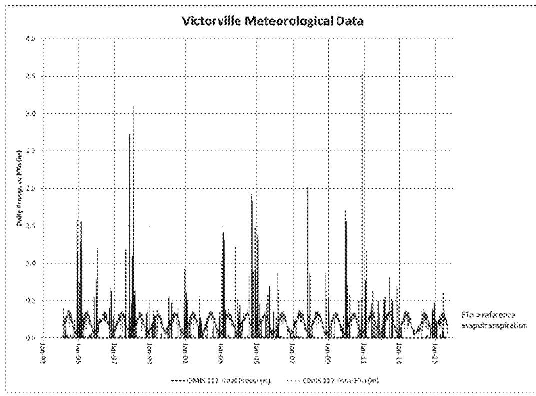
- Input temporal (daily, hourly, etc.) meteorological data on top of model
- Infiltration calculated in model by precipitation – evapotranspiration
- Recharge calculated by vadose zone water that reaches water table
- Can define various surface vegetation types, for GAFB will use sparse grass



| | Time [days] | Precip. [cm/day] | Evap. [cm/day] | Transp. [cm/day] | hCritA [cm] | Var.Fl1 [cm/day] | Var.H-1 [cm] |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.01 | 0.371 | 0.371 | 10000 | 0.361 | 0 |
| 2 | 2 | 0.01 | 0.389 | 0.389 | 10000 | 0.379 | 0 |
| 3 | 3 | 0 | 0.421 | 0.421 | 10000 | 0.421 | 0 |
| 4 | 4 | 0.07 | 0.461 | 0.461 | 10000 | 0.391 | 0 |
| 5 | 5 | 0 | 0.466 | 0.466 | 10000 | 0.466 | 0 |
| 6 | 6 | 0 | 0.554 | 0.554 | 10000 | 0.554 | 0 |
| 7 | 7 | 0.05 | 0.427 | 0.427 | 10000 | 0.377 | 0 |
| 8 | 8 | 0 | 0.546 | 0.546 | 10000 | 0.546 | 0 |
| 9 | 9 | 0.01 | 0.525 | 0.525 | 10000 | 0.515 | 0 |
| 10 | 10 | 0 | 0.395 | 0.395 | 10000 | 0.395 | 0 |
| 11 | 11 | 0.03 | 0.519 | 0.519 | 10000 | 0.489 | 0 |
| 12 | 12 | 0.97 | 0.23 | 0.23 | 10000 | -0.74 | 0 |
| 13 | 13 | 0 | 0.316 | 0.316 | 10000 | 0.316 | 0 |
| 14 | 14 | 0 | 0.435 | 0.435 | 10000 | 0.435 | 0 |
| 15 | 15 | 0 | 0.4 | 0.4 | 10000 | 0.4 | 0 |
| 16 | 16 | 0 | 0.381 | 0.381 | 10000 | 0.381 | 0 |
| 17 | 17 | 0.52 | 0.349 | 0.349 | 10000 | -0.171 | 0 |

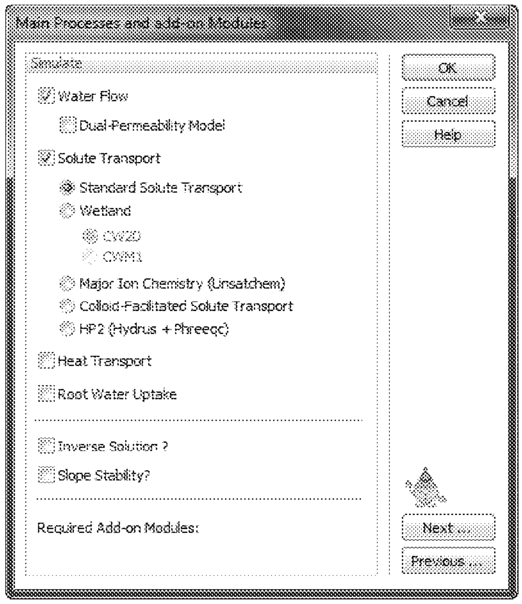
# Meteorological Input Data

- Use daily Victorville CIMIS station 117 from 1993-present
- For long-term simulations
  - Repeat CIMIS 117 data or
  - Use daily Victorville Pump Station for 1940-1993



# HYDRUS Transport Input—Solute Transport

- Various processes and solution methods
- Solute transport module accommodates retardation, equilibrium and nonequilibrium adsorption/desorption), chain decay, and colloidal transport
- Internal control on Peclet and Courant numbers to limit numerical dispersion



# Calibration

- Flow—Select wells along and near profile line and compare model results to observed water level changes over time
- Transport
  - Source area
    - No NAPL sites—Compare model results to historical groundwater concentrations
    - NAPL sites—Historical concentrations and current groundwater concentrations from LNAPL wells
  - Plume area—Compare concentrations at monitor wells along and near the profile line to model results

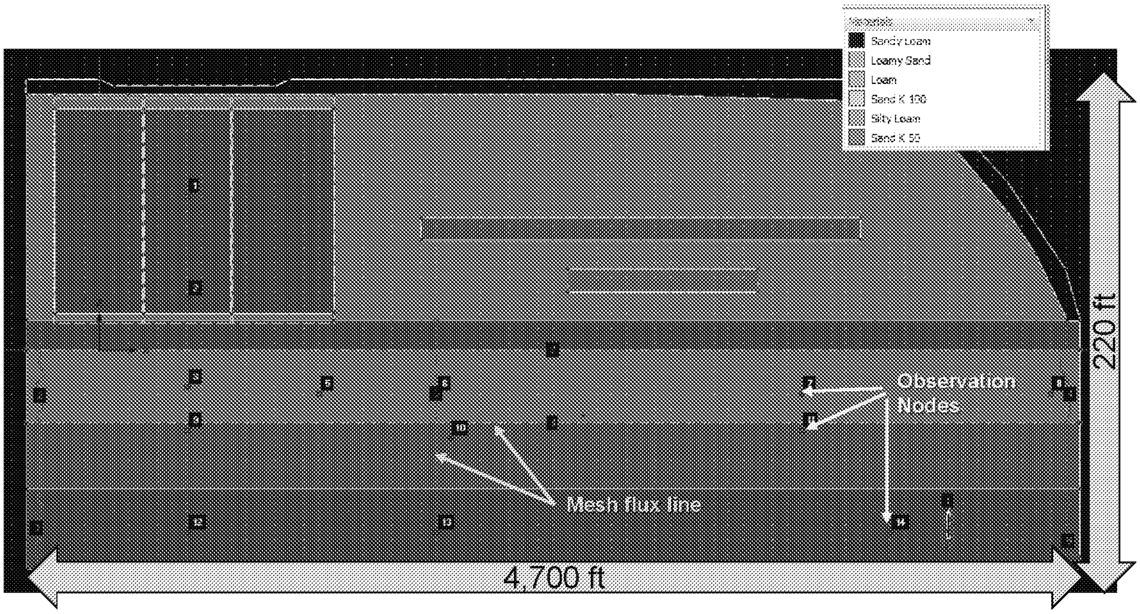
# Remediation Simulations

- Vadose zone contamination—Initial concentrations derived from soil vapor concentrations over time
- LNAPL contamination—Initial concentrations derived from groundwater concentrations over time
- Remediation concentration reductions will be simulated by observed or calculated concentration reductions depending on remedial option
- Depending on compound, decay will be included to match observed concentrations over time

# HYDRUS Model Example

- 2D X-Z profile section extends from ground surface down through top portion of Lower Aquifer
- Illustrative generic profile for FT082 (final model will incorporate more lithologic detail)
- Unsaturated flow parameters derived from soil type
- Surface soil from SSURGO soils database (U.S. Dept. Ag.)
- Generalized lithology from 3D lithologic model
- Gradients and hydraulic properties from OU1 MODFLOW model (2009)
- Contaminant source derived from fire-training operations and assumed source mass loading including enhanced infiltration from fire training over time (30 years)

# Example Model Soil Type and Observation Nodes

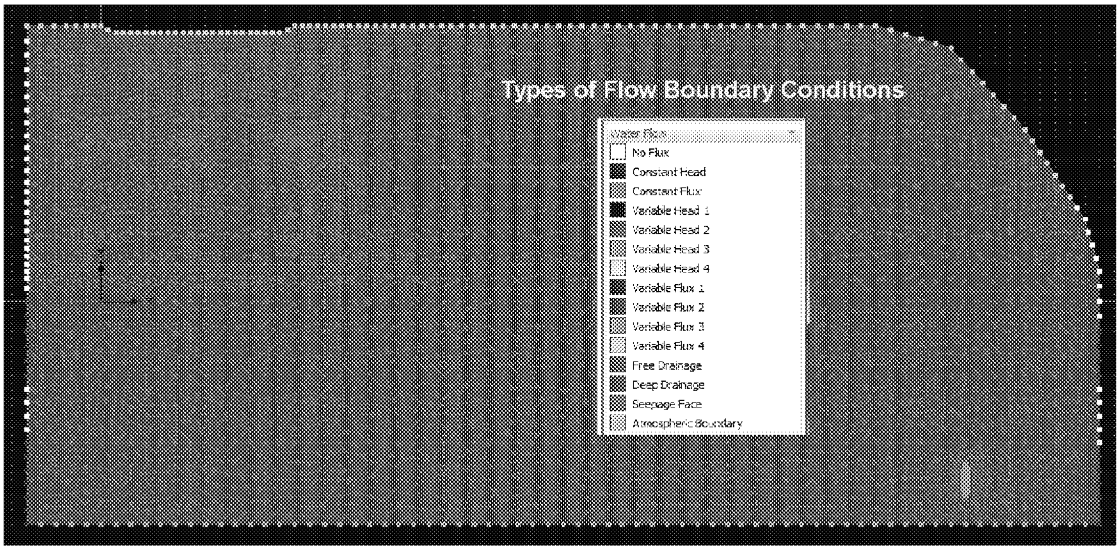


# Example Model Soil Properties

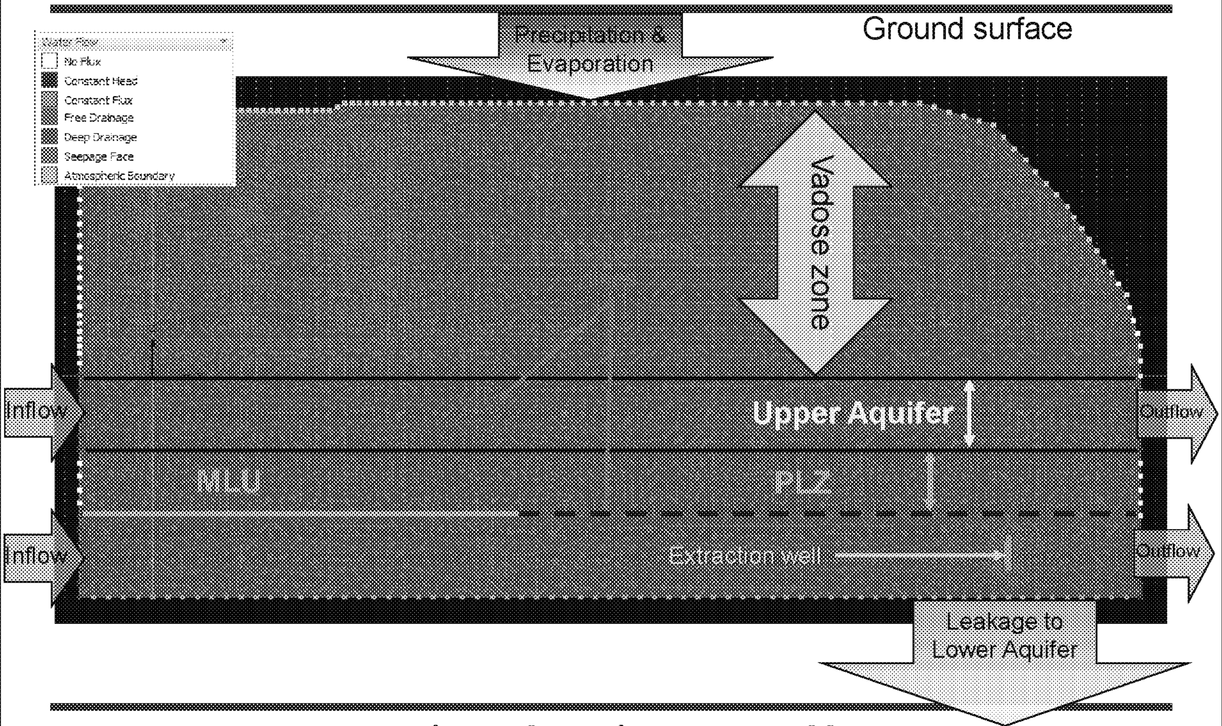
| Soil Type | Qr (frac) | Qs (frac) | Alpha (1/cm) | n(-) | Ks (cm/d) | l (unitless) | Ks (cm/sec) | Ks (ft/d) | Zone |
|---|---|---|---|---|---|---|---|---|---|
| Loam | 0.078 | 0.43 | 0.036 | 1.56 | 24.96 | 0.5 | 2.89E-04 | 0.82 | Sandy silt units |
| Sandy Loam | 0.065 | 0.41 | 0.075 | 1.89 | 106.1 | 0.5 | 1.23E-03 | 3.5 | Silty sand units |
| Loamy Sand | 0.057 | 0.41 | 0.124 | 2.28 | 350.2 | 0.5 | 4.05E-03 | 11 | Fine-grained sand |
| Sand | 0.045 | 0.43 | 0.145 | 2.68 | 712.8 | 0.5 | 8.25E-03 | 23 | Sand above UA |
| Sand Hi K | 0.045 | 0.43 | 0.145 | 2.68 | 1500 | 0.5 | 1.74E-02 | 49 | Not used |
| Silty Loam | 0.067 | 0.45 | 0.02 | 1.41 | 10.8 | 0.5 | 1.25E-04 | 0.35 | MLU |
| Sand K 100 | 0.045 | 0.43 | 0.145 | 2.68 | 3000 | 0.5 | 3.47E-02 | 98 | Main UA/LA sands |

| Parameter | Description |
|---|---|
| Qr | Residual soil water content, $\theta_r$ |
| Qs | Saturated soil water content, $\theta_s$ |
| Alpha | Parameter $\alpha$ in the soil water retention function [$L^{-1}$] |
| n | Parameter $n$ in the soil water retention function |
| Ks | Saturated hydraulic conductivity, $K_s$ [$LT^{-1}$] |
| l | Tortuosity parameter in the conductivity function [unitless] |

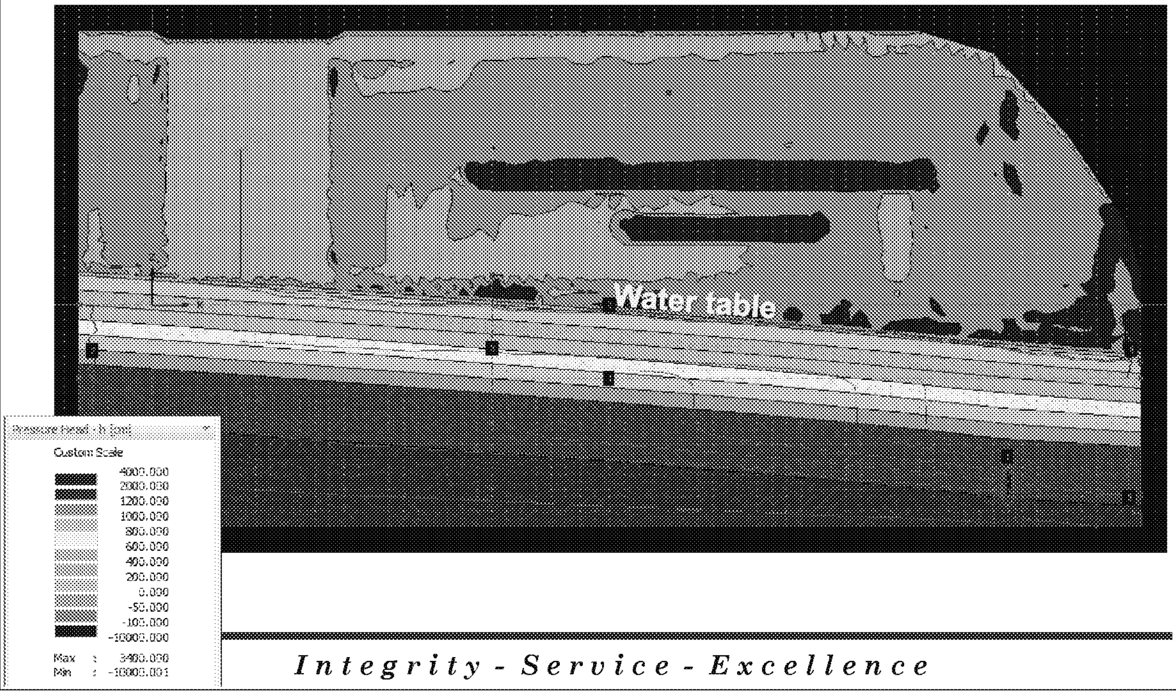
# Finite Element Mesh (12,000 elements)



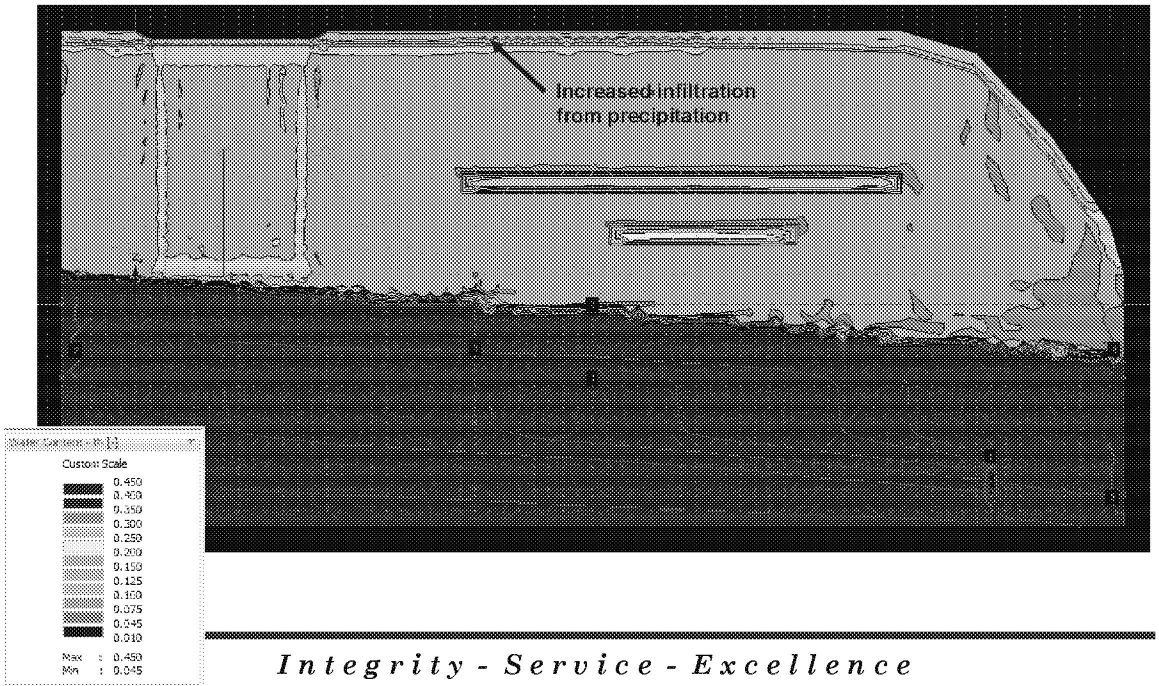
# Example Model Boundary Conditions



# Example Model Results—Pressure Head (cm)

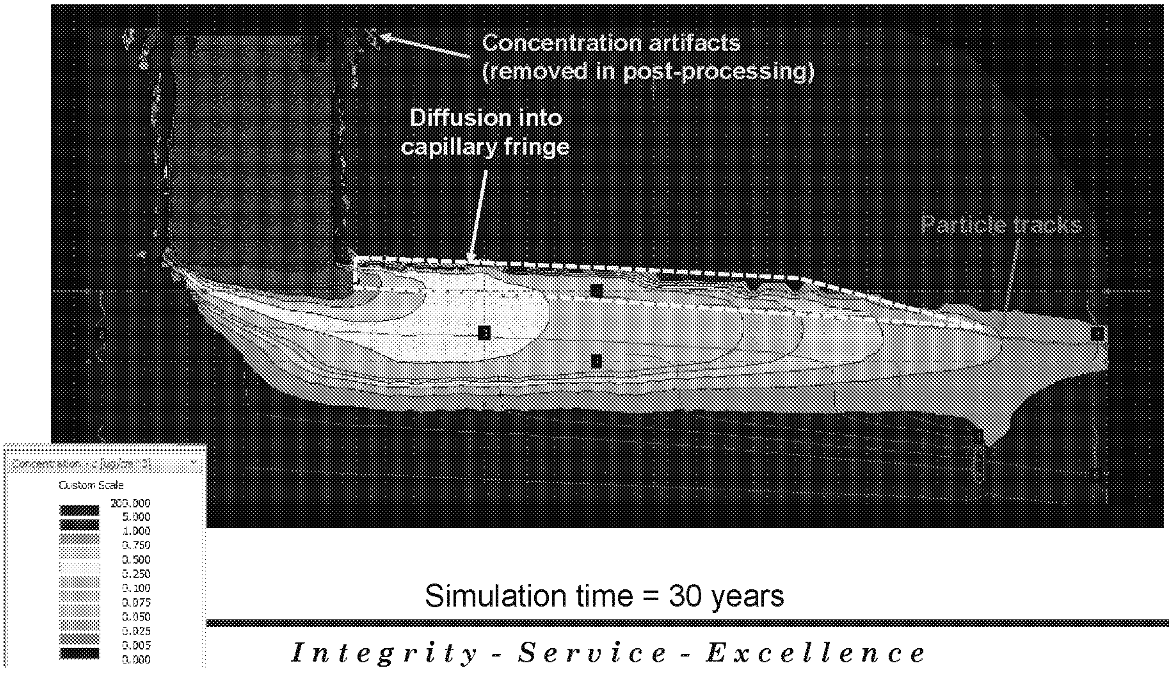


# Example Model Results—Water Content (fraction)



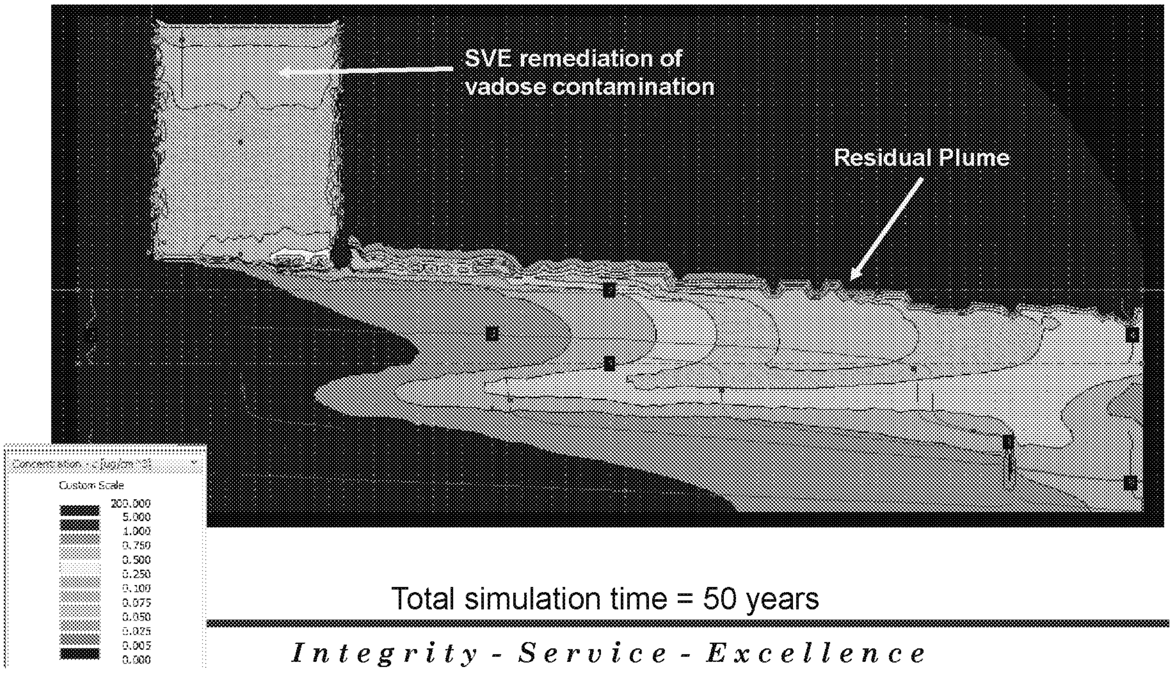
# Example Model Results—Solute Transport (mg/L)

Water concentrations




Simulation time = 30 years

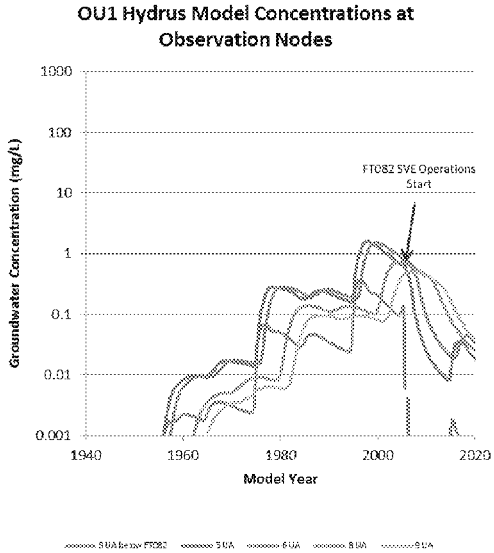
# Concentrations after Vadose Zone Remediation



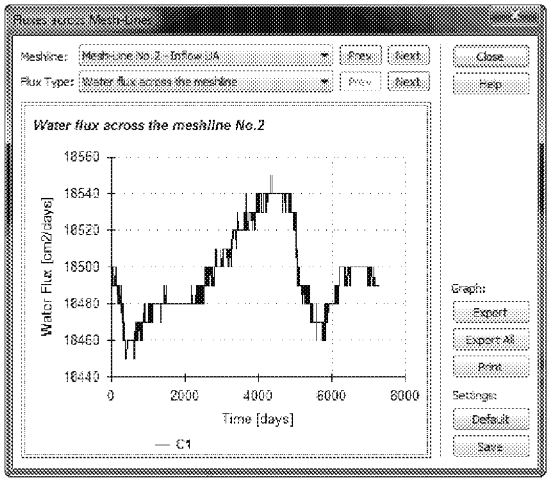

Total simulation time = 50 years

# Example Output

## Concentrations at Observation Nodes

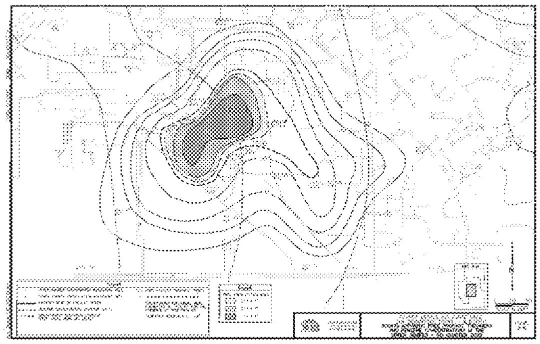



## Recharge into Upper Aquifer



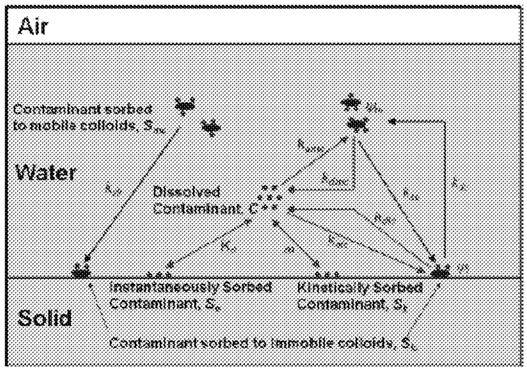
# Simulation of Sites with Vadose Zone and LNAPL Contamination

- Vadose zone mass-loading will be simulated as in previous example
- LNAPL area will be simulated as area of constant concentration
- Source—loading groundwater concentrations derived from water samples from selected LNAPL wells



# HYDRUS Model for Dieldrin Colloidal Transport Analysis

- HYDRUS C-Ride variably saturated porous media colloidal transport module used for Dieldrin migration modeling
- Based on mass balance of colloidal and dissolved contaminant species
- Includes colloidal straining (stuck on soil particles), sorption on carbon, and exclusion processes (flow through larger pores)
- HYDRUS calculations track colloids, solute sorbed on colloids, and solute in water



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# OT071 Dieldrin Model Parameters

- Hydraulic parameters from site lithology and previous modeling
- Colloidal transport parameters from published studies and various HYDRUS examples
- Calibrate to Dieldrin application timing and observed groundwater plume

# Path Forward

- Obtain agreement that the Air Force can use HYDRUS model code for source-area remediation simulations
- Conduct SS030 modeling
  - Example for other sites as it has both vadose zone and LNAPL source areas
  - Have periodic model updates and technical discussions via on-line conference calls
  - Submit modeling report for review
- Expand to other sites after SS030 discussions